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Towards low-threshold, real-time solar neutrino detectors

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Abstract

We discuss an alternative approach to the detection of solar neutrinos using a coarsely segmented detector based on inverse-beta decay onto ^{160}Gd or ^{176}Yb. While it is known that similar approaches, already discussed in the literature, can in principle provide low-threshold, real-time energy spectroscopy with intrinsic background rejection features, the concepts presented here make this scheme possible with lower background and current technology.

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Neutrinos from the sun have been observed by a number of detectors over the past 30 years. While it is generally accepted that the Standard Solar Model (SSM) [1] has been remarkably successful in describing the nuclear fusion in the sun, large discrepancies remain between experimental data and the SSM predictions (see, Ref. [2]). Indeed, it is quite possible that the solar neutrino anomaly may be due to phenomena related to intrinsic neutrino properties. Detailed understanding of solar neutrinos is limited by our ability to collect high-quality data on the subject, so that further progress in the field requires the development of qualitatively new experimental tools.

According to the SSM the solar neutrino flux is dominated by the low-energy (0–0.4 MeV) pp component which has been measured by the Gallex and SAGE experiments. These two experiments, however, can only measure the integrated flux above an energy of 0.23 MeV. Similarly, the pioneering chlorine experiment at Homestake integrates all energies above 0.81 MeV, hence including most of ^{7}Be along with pep and ^{8}B fluxes. Water Cherenkov detectors like (Super) Kamiokande [3][1] and SNO [4], and large scintillation detectors like Borexino [5] and KamLAND [6] can do real-time spectroscopy but with a resolution limited by the electron scattering kinematics. More important their thresholds are too high to be sensitive to pp neutrinos.

In order to make a qualitative improvement in the field one has to find a detection scheme able to provide real-time detection with low threshold, to include the pp flux, and good energy resolution. The main obstacle in achieving these goals

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[1] For considerations on the Kamiokande and Super-Kamiokande detectors, see for example Ref. [3].

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comes from the formidable backgrounds from natural radioactivity that severely limit the energy threshold of scintillation and Cherenkov detectors. Such backgrounds force one to adopt extremely large shielding volumes and levels of U, Th, ^{40}K and ^{14}C in the active scintillation fluid that are at the very limit of what is measurable [5,6]. While Borexino has demonstrated their target contamination levels (10^{-16} g/g for U/Th, 10^{-18} g/g for ^{40}K and 10^{-18} for ^{14}C/^{12}C) in a small size test facility [7] the possibility of achieving similar values in a few-hundred-times larger detector remains to be demonstrated. Indeed it is quite clear that backgrounds (in particular from ^{14}C) grow too rapidly below 400 keV to try to perform any measurement below the pp threshold.

A new detection scheme able to fulfill all the requirements mentioned above has been recently proposed [8]. In such a scheme, ^{160}Gd and ^{176}Yb are used as targets for solar neutrino absorption through the inverse-β decay reactions

$$\nu_e + {}^{160}\mathrm{Gd}({}^{176}\mathrm{Yb}) \rightarrow e^- + {}^{160}\mathrm{Tb}^*({}^{176}\mathrm{Lu}^*).$$

The ^{160}Tb*(^{176}Lu*) states de-excite with a lifetime of 87 ns (50 ns) emitting γ's of 63.7 keV (72 keV). The threshold of these reactions is 0.24 MeV (0.30 MeV), well below the maximum pp neutrino energy, and while the *total* neutrino energy can be measured from the energy release by electron and γ in the inverse-β process, the fast correlation time between electron and γ emission provides a powerful method for suppressing backgrounds. The target isotopes would be dissolved in liquid scintillator to provide high detection efficiency and good energy resolution for the low-energy processes described. While precise measurements of the neutrino capture cross sections for the above reactions will be essential for a successful experiment, it is suggested [9] that the log *ft* are in the range 3.5–4.2 so that a 100 t scintillation detector, loaded with 10% of natural Gd or Yb would give a signal of the order of 1 event/d. As suggested in Ref. [8] spatial segmentation of the detector provides an additional suppression of the background since electron and γ emission in the neutrino capture processes are bound to originate from the same region of space.

In this letter we will point out some difficulties with this scheme and suggest ways to bring this powerful idea to full fruition.

The addition of Gd (Yb) to the scintillator poses two main problems:

- while several chemical processes able to load liquid scintillators with rare earths and other heavy elements are known [8,10–12] we believe that it is quite unlikely that at the high loading required (10–30%) the scintillator can still be transparent and stable enough to perform a long-term experiment with a detector of the size required. The last generation of reactor neutrino oscillation experiments, and in particular the Palo Verde detector, are very similar in size and need to detect very low-energy events like in the proposed scheme. Both Chooz [11] and Palo Verde [10] used 0.1% Gd loading and, while attenuation lengths of $\simeq 10$ m and stable operation were finally obtained, it is unlikely that an increase in loading of few hundred times could still give a scintillator capable of detecting a fraction of 100 keV at several meter distance for many years.
- it is known that the purification of rare earths from heavy metals such as Th and U is relatively more difficult than in the case of the organic components of scintillators. Hence, a highly loaded scintillator is bound to be substantially "dirtier" than the organic components alone. Some measurements [13] of high-quality commercial Gd oxides and nitrates give U and Th contaminations at the level of 0.8–20 ppb. If we aggressively assume a factor of ten improvement on the best figure (0.1 ppb) we still obtain a 10^{-11} g/g contamination for the whole liquid scintillator (at 10% loading). While the time and spatial correlations provide uncorrelated background suppression factors of, respectively, 10^8 and 10^4, such reductions do not apply to decay sequences from natural isotopes having lifetimes in the 10–1000 ns range. Unfortunately, one such cases is present in the ^{232}Th decay chain

  $$^{212}\mathrm{Bi} \rightarrow {}^{212}\mathrm{Po}(299\ \mathrm{ns}) \rightarrow {}^{208}\mathrm{Pb}.$$

  While the Bi β-decays with a Q value of about 2.5 MeV the Po decays with a 8.8 MeV α. We find

that substantial background arises from the cases in which the Po decay occurs near the walls of the container so that part of the ionization from the α is lost into passive material. We note here that, while the α energy is well above the energy expected for neutrino events, scintillation light is generally quenched by a large factor of order 10. Pulse shape analysis may improve slightly the situation but will certainly be hampered by the non-optimal light collection geometry. Our detailed simulation predicts a rate of mis-identified events of 10/d for a cell cross-section 20×20 cm^2 (and the mass and contamination figures indicated above). It is interesting to note that this background derives *only* from the outermost layer of scintillator (about 100 μm thick) that can give non-contained α's. Hence, while finer segmentation improves the rejection of the uncorrelated backgrounds, at the same time it increases the surface to volume ratio making the effects of the Bi–Po background worse.

Both difficulties would be completely eliminated by using transparent and active material, such as plastic scintillator, as the walls of liquid scintillator cells. The plastic scintillator would serve two distinct purposes:

(1) it would fully contain the α's produced by the impurities in the Gd,
(2) it would act as a wavelength shifter and absorb, re-emit and transport the light produced by scintillation in the Gd-doped scintillator.

Fig. 1 shows the basic principle of the detector. Plastic wavelength shifters have been used in a similar fashion in a number of cases [14,15] mainly in order to reduce the active surface (and hence, in general, the noise) of the light detector in scintillation counters. In our scheme an appropriate fluor in the plastic scintillator would act as a shifter for the light produced with shorter wavelength in the liquid scintillator. The longer wavelength light will then be transported inside the plastic allowing us to tolerate loaded scintillators with light attenuation length of the order of the transverse cell size (i.e. ~ 50 cm). Plastic scintillators with 5 m light attenuation length are common and commercially

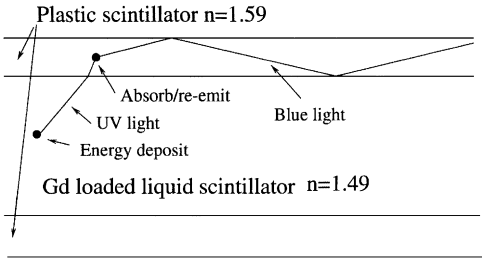

Fig. 1. The basic principle of the detector (dimensions not to scale).

available [12]. The use of a complete plastic scintillator (as opposed to a simple shifter) essentially provides a fully active medium with cleaner conditions at the surface where α's are difficult to reject. Photo-detectors (assumed to be conventional photomultipliers in our analysis) should be fitted onto the ends of the plastic scintillator walls only. A further potential advantage, that we do not study in detail here, may lay in better pulse-shape discrimination obtained by guiding the light through a smaller cross-section channel (the plastic scintillator wall as opposed to the bulk liquid).

In order for this system to work properly some substantial fraction of light has to be extracted from the liquid into the plastic and then be trapped in there. This can be achieved by a proper match of refractive indices, with $n_{\text{liquid}} < n_{\text{plastic}}$ (and, trivially, $n_{\text{air}} < n_{\text{plastic}}$). Although a careful R&D study may provide better figures here we assume $n_{\text{liquid}} = 1.49$ and $n_{\text{plastic}} = 1.59$ as it is the case for standard commercial products. We perform a full Monte Carlo simulation using GEANT3 to study in detail the signal detection and the resolution and to estimate the background and the light collection efficiency. Each detector cell is $20 \times 20 \times 500$ cm^3, a total of 625 cells constitute the detector with total dimensions of $5 \times 5 \times 5$ m^3 and a total mass of 125 t. The plastic scintillator walls are assumed to be 1 cm thick. Furthermore, we assume the yield of the loaded scintillator to be 5000 photons/MeV (roughly 50% of standard liquid scintillators) and the conversion quantum efficiency of the scintillating walls 80%. Finally, we assume that the light attenuation length of the loaded (plastic) scintillator is 0.5 (5) m. These factors, together with the

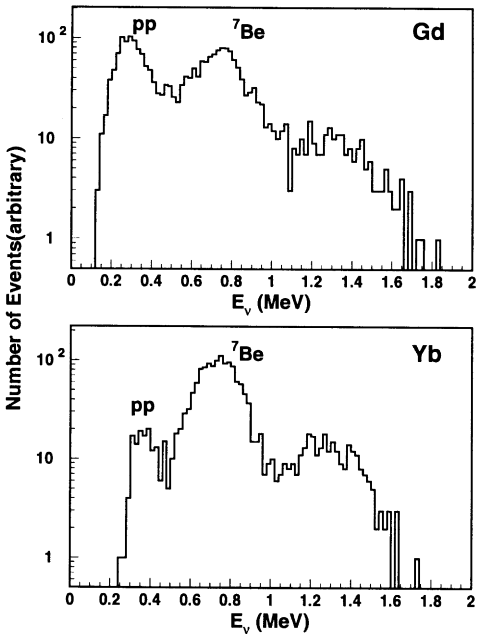

Fig. 2. Simulated energy spectrum of ν_e from the detector concept presented. The lower threshold in Gd gives a substantially better pp-neutrino detection.

optical efficiency of the system and quantum efficiency of a bi-alkali photocathode, give 1.8 PE/50 keV at each end of a detector cell. This is sufficient to make a coincidence of the signals from the two ends to reduce the photo-detector noise. Fig. 2 shows the simulated energy spectrum of ν_e as would result from this system. Both pp and ^{7}Be peaks are visible. We note here that Gd gives a substantially better pp detection due to the lower threshold.

Table 1 gives our estimate for the uncorrelated background coming from the natural radioactivity. While the rate N_1 corresponds to energies between 0.04–2 MeV which could mimic the prompt β, N_2 corresponds to energies between 0.04–0.16 MeV which could mimic the delayed low-energy γ. Using a coincidence window of 250 ns, and a space reduction factor of 10^{-4} (derived from the transverse segmentation and a longitudinal resolution of $\simeq$ 50 cm), we obtain a background rate of 0.1/d, well below the signal rate. The longitudinal position resolution is conservatively derived from the performance of the Palo Verde detector [16] that

Table 1

Isotope	Purity	N_1 (Hz)	N_2 (Hz)
^{238}U	10^{-11} g/g	150	15
^{232}Th	10^{-11} g/g	31	2.6
^{40}K	10^{-11} g/g	250	12
^{222}Rn	0.1 Bq/m^3	88	6
^{14}C	10^{-18} ^{14}C/^{12}C	14	14
Total		533	50

has a very similar configuration. We note here that our table does not include backgrounds arising from possible ^{176}Lu and ^{147}Sm contamination in the Yb and Gd compounds. Special chemical processing will have to be devised in order to make our scheme (and probably any other scheme based on a rare-earth target) viable [8].

The correlated background from the Bi–Po chain is now negligible provided that the Th concentration in plastic scintillator is below 10^{-13} g/g. This requirement is readily achievable with commercial materials. We note here that, while a somewhat similar scheme employing wavelength-shifting fibers was proposed in Ref. [17], our purpose is to efficiently extract light from a large detector while reducing the background from correlated sources. This second purpose in fact substantially impacts the detector optimization, making a very fine segmentation a losing strategy.

The chemical compatibility between loaded liquid scintillators and a plastic scintillator container may appear to be problematic since aromatic solvents (that are generally used to achieve high loading) are aggressive, in long periods of time, for polystyrene-based plastics. While it is quite possible that a proper study will be able to produce a pair of compatible materials we briefly describe here three alternative techniques to avoid the problem altogether.

- Very thin (few μm thick) fluoropolymer coatings are available in completely transparent form (over 95% transmission in the near UV) as separate films to apply to the surface to protect or through a chemical deposition process. Such fluoropolymer coatings would chemically isolate

the liquid scintillator from the plastic still retaining all the features described (optics and almost full α detection).

- Highly loaded liquid scintillator cocktails are possible by forming a micro-emulsion of a scintillating fluid (containing heavy and hence non-aggressive aromatics) with a water-based solution of the rare-earth element [18,19]. Such systems, commonly used in the life sciences typically have poor light attenuation lengths that are, however, perfectly adequate in our case. Indeed refractive indices as low as 1.44 can be achieved with this technique [20].
- The Gd (Yb) loaded part of the detector could also be built out of plastic scintillator. In this case there would probably be a very small air gap between the loaded core and the unloaded "box" around and, although the optics will be somewhat different, we believe that our conclusions would still hold.

In summary, we have presented an alternative approach to the detection of solar neutrinos using a coarsely segmented detector based on inverse-beta decay onto ^{160}Gd or ^{176}Yb. Such an approach would allow low-threshold, real-time energy spectroscopy with technology available today. The correlated signature of the neutrino events would allow effective reduction of random backgrounds, while the remaining correlated backgrounds will be eliminated by the particular detector configuration.

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